Towards Designing Graceful Degradation into Trajectory Based Operations: A Human-Machine System Integration Approach

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One of the most fundamental changes to the air traffic management system in NextGen is the concept of trajectory based operations (TBO). With the introduction of fundamental change, system safety and resilience is a critical concern, in particular, the ability of systems to 'degrade gracefully'. In order to design graceful degradation into a TBO envrionment, knowledge of the potential causes of degradation and appropriate solutions is required. Previous research has predominantly explored the technological contribution to graceful degradation, frequently neglecting to consider the role of the human operators in an environment in which humans, especially air traffic controllers, play a safety critical role. In addition, the environmental context in which the technological or human breakdowns occur also play a critical role in how well the system can degrade gracefully, which is also neglected in the literature. These oversights are out of step with real-world operations, and potentially limit an ecologically valid understanding of achieving graceful degradation in an air traffic control environment. Therefore, an integration approach to the human-machine system must be applied in order to achieve graceful degradation. The following literature review aims to identify and summarize the literature to date on the potential causes of degradation in air traffic control and the solutions that may be applied within a TBO context, with a specific focus on the contribution of the air traffic controller. A framework of graceful degradation, developed from the literature, is presented. The framework encompasses the potential impact of technology or human operator breakdown, as well as the complexity of the air traffic environment at the time of the breakdown, and categorizes them into different phases of detection and recovery. The aim of the framework is to develop research questions and design solutions to develop a resilient TBO system and procedures using a holistic view of human-machine system integration.

I. Introduction

ACROSS both Europe and the USA the continuous growth in air traffic has resulted in air traffic management (ATM) technological systems operating beyond capacity [1, 2]. The Single European Sky Action Research (SESAR) program in Europe, and the Next Generation (NextGen) program in the US, are redefining air traffic management operations in response to the increasing operational demands [3, 4].

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One of the most fundamental changes to the traffic management system is the use of trajectory based operations (TBO) [3, 4]. TBO generates a shift from manual, tactical air traffic control, to more automated, strategic traffic management. TBO envisions that aircraft will fly four dimensional (latitude, longitude, altitude, and time) trajectories that are often pre-negotiated and managed during flight via time constraints and metering. One of the key aims of TBO operations is to "enhance system efficiency by making use of narrower tolerances, better information, and tools designed to assist projections and decision making" [4, pii]. The implementation of TBO necessitates significant change to the current air traffic management system. Technology and automation advancements for both the air and ground are required as enablers for TBO [e.g. 5]. In addition, human operators' roles may change [4]. For example, air traffic controllers may be responsible for managing aircraft trajectories with less buffers and tighter precision compared to the present day [4], whilst using, and supervising, automated tools [6].

With the introduction of such fundamental change to the ATM system, system safety and resilience [e.g. 7] is a critical concern. An important element of maintaining system safety and resilience in air traffic is the ability of systems to 'degrade gracefully'. A system that is designed to degrade gracefully can "tolerate failures by reducing functionality or performance, rather than shutting down completely" [8, p111], a necessity in a domain in which there are no physical barriers or defenses to protect aircraft in flight.

In order to design graceful degradation into TBO, knowledge of the potential causes of degradation and graceful recovery solutions is required. Research specific to graceful degradation in a TBO environment is scarce. Graceful degradation literature from other domains must therefore be summarized to gain further understanding of how graceful degradation in TBO may be created. In addition, the research that is available predominantly focuses on technological degradation and recovery with only sporadic research on the specific contribution of the human operators in the system, such as air traffic controllers (ATCOs), traffic flow managers, pilots, and airline dispatchers. In particular, ATCOs play a safety critical role in detecting and recovering a degraded state due to technological failures or off-nominal events. The gap in understanding of the contribution of the human operator is out of step with real-world operations, and potentially limits an ecologically valid understanding of graceful degradation in air traffic control (ATC). In order for graceful degradation to be achieved in TBO, it is essential that the potential causes of system degradation and associated solutions are identified, and that ATCOs are considered as part of a gracefully degrading system [9]. The following literature review aims to begin to address these gaps. The literature review identifies and summarizes the literature to date on the potential causes of degradation and the solutions that may be applied to a TBO context. A framework of graceful degradation, developed from the literature, is presented. A specific focus is given to the benefit of utilizing a human-machine system integration approach to gain insight into this complex area.

II. Method

A. Aims

The aim of this paper is to provide a literature review of research that is relevant to developing graceful degradation solutions in a TBO environment. A second aim is to provide a framework to organize the literature in ways that would allow engineers and human factors researchers to identify and evaluate human-machine integration issues within the TBO context. Throughout the paper, a distinction is made between the human-machine system terminology that incorporates the role of the human operator as well as the interaction between the human operator and ATC technologies and automation, and the narrower definition of a technological system, which refers only to the technologies used in an ATC environment. The term 'system' is used to refer to the wider human-machine system, whilst 'technological system' refers specifically to the technological and automation-based systems that enable the provision of ATC services.

The aims of the following literature review were threefold. The first aim of the literature review was to summarize the research to date that identified causes of ATM related system degradation, and associated solutions of degradation, that were applicable to the TBO environment. An additional aim was to identify the role of the human operator, specifically, ground-based air traffic controllers (ATCOs), in a gracefully degrading system. A further aim was to develop a summary framework of graceful degradation based on the available literature, with the ultimate intention to identify literature gaps relating to specific areas, and guide future research.

B. Design and Procedure

The literature search was focused on papers that investigated one or more of the following topics:

1. TBO
2. Graceful degradation
3. Causes of system degradation
4. Preventative measures of system degradation
5. Recovery measures for degraded systems

Papers were selected according to specific criteria. All papers had been published in peer-reviewed journals or conference proceedings, or were reports from relevant organizations such as the FAA, JPDO and EUROCONTROL. The quality of the studies was therefore independently evaluated by subject experts. In line with one of the aims of the literature review, particular focus was given to including papers that investigated the role of the human operator in TBO and graceful degradation. The authors acknowledge that many human operator roles interact with the new TBO system; however, particular attention was given to the role of ground-based air traffic controllers.

Following [10]'s methodology, the abstract of each paper was read prior to inclusion to ensure that the article adhered to the selection criteria and was relevant to the study. The selected papers were not restricted to a specific domain although preference was given to papers focused on TBO and ATM. Due to the relative lack of research investigating graceful degradation of TBO, this decision was necessary in order to provide a comprehensive and informed review of research on degradation causes and solutions. The papers selected for review were also not restricted by date of publication, measure or method differences. This decision was made so that a larger number of relevant papers that investigated the relationship between specific human factors could be included in the review, generating a wide review of this research area. Papers were identified from a key-word based search of electronic databases (Ergonomics Abstracts, PsychINFO, Science Direct, Scopus and Web of Science) and a search engine (Google Scholar). The procedure followed was similar to the search procedure methods used in other literature-based analyses, such as [10, 11].

III. Trajectory Based Operations

Trajectory based operations (TBO) is the proposed future approach to air traffic management, designed to increase the efficiency, predictability and capacity of the current strained airspace [4]. The concept of TBO, as outlined by [4]'s CONOPs, is based on the management of air traffic via four dimensional trajectories. Trajectories are developed from gate to gate, in other words, setting the entire aircraft route, and will be negotiated and approved between airspace users (i.e., the airline operators) and air navigation service providers (ANSPs) prior to the aircraft taking off. Trajectories are expected to be strategic and computed automatically. The computation of trajectories takes into account several sources of information, including the user's preferred route, restricted airspace, and weather, so that the trajectories that are developed are as efficient as possible [4,12]. ATCOs are expected to manage aircraft on trajectories via time constraints rather than traditional waypoints, and manage trajectories during flight in response to dynamic airspace conditions.

A. ATM Technology in Trajectory Based Operations

In order for the TBO concept to be realized, air and ground technologies that include advanced automation are required as enablers. Predominantly laboratory-based research has furthered the development and application of advanced technologies [e.g. 4, 5, 12, 13, 14], although not all researched technologies are yet included in [4]'s CONOPs. For example, [5] investigated trajectory-based automated separation assurance ground tools using three, incremental, human in the loop simulations. Automated separation assurance was assessed via safety (e.g. frequencies of loss of separation) and efficiency (e.g. delay added to original trajectories) measures, as well as self-reported ATCO workload measures. Findings provide insight into the level of automation that is most positive in terms of trajectory based operations and ATCO workload, furthering insight into the design and development of enabling technologies.

B. The Role of the Human Operator in Trajectory Based Operations

For the mid-term TBO timeframe, human operators, such as ATCOs, pilots, and traffic managers are envisioned to remain actively involved in air traffic management [4]. However, roles are expected to change significantly. TBO "represents a fundamental shift of Air Traffic Management (ATM) from control through tactical, verbally issued instructions and clearances to trajectory-based management of aircraft" [4, p6] which has the most obvious implications for pilots and air traffic controllers.

The implications of the role change are especially significant for ATCOs. ATCOs are expected to change control strategy "from a less efficient manual and tactical operation to a highly efficient strategic and automated operation" [4, P6]. Specifically, the latest TBO CONOPS [4] suggests that ATCOs will need to control using more automated tools and decision support technologies that will guide expected actions. It has therefore been suggested that ATCOs' will take a more supervisory role of advanced automation compared to current day operations [6], with an increased focus on strategic control and a significant reduction of tactical control maneuvers, such as vectoring, to maintain separation assurance. ATCOs are expected to ensure flights meet time constraints of the specific trajectories and manage trajectories around weather and other airspace constraints.

IV. Resilience and Graceful Degradation

Safety is a critical concern within the air traffic domain. Air traffic management is a safety critical domain that is highly human centric. There are no physical barriers of defense, and human operators are currently responsible for the safety and efficiency of air traffic [15]. With a large amount of change to ATM operations planned with the introduction of TBO, system safety is a dominant issue of consideration. Due to the safety critical nature of ATC, it is essential that ATC systems and technologies are resilient in order to maintain safety. Resilience is the ability of a system to "adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" [7, p1].

One specific aspect of achieving resilience that is of particular relevance to TBO is the notion of graceful degradation. Graceful degradation may be defined loosely as a system that "tolerates failures by reducing functionality or performance, rather than shutting down completely" [8, p111] as opposed to a brittle system which can suddenly 'break', creating a 'cliff-edge effect' [16]. Graceful degradation is often defined in association with technology only, such as "an ideal gracefully degrading system is partitioned so that failures in non-critical subsystems do not affect critical subsystems" [8, p156]. Other definitions refer to graceful degradation specifically within the context of fault tolerant technologies [17]. For the purposes of the current literature review however, a wider definition of graceful degradation as a system-wide outcome is adopted, including elements of technology and human operators, such as the definition by [18] "to gracefully degrade, the system must maintain safety performance requirements in the presence of faults or failures while and until demand is reduced to performance levels commensurate with the degraded capabilities" [p5].

A. Graceful Degradation in TBO

Within TBO, the concept of graceful degradation is critical to providing safe operations. [18] suggest that the number one vulnerability of complex systems is the "lack of graceful degradation" [p5]. In order to design resilient systems that are capable of graceful degradation, it is essential to understand the key causes of system gradation, as well as the possible mitigations to degradation, and applicable recovery mechanisms if the system does degrade. Within the TBO field, there is emerging research of potential causes of system degradation.

B. TBO Graceful Degradation: A Research Gap

Research relating to graceful degradation in TBO has predominantly focused on the investigation of technological systems. For example, new technologies must be combined with legacy technologies, potentially creating a risk of degradation [9]. [13] gives the example of integrating a new decision support tool with legacy operational tools, which initially resulted in generating conflicting advisories for the ATCOs.

Traditionally, humans have not received much focus in graceful degradation research (e.g. [12]). Literature considering the interaction of ATCOs with TBO, and the subsequent contribution to graceful degradation and resilience of TBO, is especially sparse, with [19] suggesting that there is an "ill-defined understanding of the human factors interactions within the TBO environment" (p4517). In addition to a lack of research on the direct impact of TBO on ATCOs, there is also a relative lack of research on the human-machine interface of new TBO technologies. [6] points out that the vast enabling technology and advanced automation tools for TBO are routinely designed without significant attention to the human-machine interface, resulting in the potential for human error and performance-related incidents. An example of this situation can be seen in an investigation of a newly developed autopilot technology for a flight deck [20]. The new technology had been associated with an increase in pilot errors, such as incorrect altitudes. [20] found that the majority of errors could be attributed to the interface of the technology for the pilot, and when the pilot interface was changed in line with research findings, errors were significantly reduced [21].

C. The Importance of ATCOs in Understanding Graceful Degradation for TBO

Such focus in the literature on technologies has led to a greater understanding about the potential causes of technology-related degradation. However, considering the safety critical role of ATCOs in air traffic management, the gap in research of the contribution of ATCOs to graceful degradation of a TBO system is out of step with real-world operational environments, and subsequently, limits the ecological validity of existing research. This knowledge gap also results in a limited understanding of the impact of TBO on ATCOs, although there are emerging suggestions that TBO may create a negative impact on ATCO workload due to malfunctioning technologies, inconsistent advisories [13], off-nominal events with greater traffic, too stringent time constraints [6] and lack of flexibility. Finally, there is also limited research regarding the influence of ATCOs on a gracefully degrading system, both in terms of potential triggers of degradation, and supportive recovery mechanisms.

A detailed illustration of the importance of considering the ATCO to understand and create graceful degradation in TBO is shown with the situation of increased automation in ATCO tools [4]. It has been well documented that humans (including ATCOs) can be challenged by monitoring or supervising automation (e.g. [22, 23]), resulting in vigilance and situation awareness issues, and potentially leading to a human error and even a performance-related incident. The more a human operator is 'out of the loop', the challenges, and potential risk, increase if the human is required to take over from the automation. As automation is rule-based, there is a significant likelihood that ATCOs will need to override the automation during an off-nominal situation, or take manual control if the automation cannot facilitate the situation. If the automation has been designed so that the ATCO is 'out of the loop', the ATCO will need time to build a picture of the current situation, identify any problems, and formulate a plan, resulting in slower resolutions action compared to if they were fully engaged in the control task [6]. This time delay may have safety critical implications. Depending on the level of automation visibility the ATCO may not even be aware of the issue, and so will either be dependent on the automation to highlight the need for involvement, or will need to identify the issue through other mechanisms, before a resolution action can even be formulated.

Increased automation can create a second challenge. One of the purposes of automation in ATM is to increase airspace capacity through the reduction of ATCO workload and increased efficiency [6]. In nominal situations, aircraft can be managed with a reduced safety buffer and tighter precision [4]. However, if this enabling automation technology is degraded, there is a critical question of whether the ATCO could safely manually control the number of aircraft in the sector, considering that the number of aircraft could only be safely increased because of the availability of the automation. Emphasizing this point further, [18] suggest that the second most critical vulnerability of a complex system is technological or automation-related elements that exceed human operator capabilities, and asserts that such systems "must not cease operating under conditions that exceed human performance" (p5). [18] provides an example of this vulnerability with a pilot's autopilot, which operates until a situation cannot be processed by the rule based algorithms, and automatically disconnects, "leaving a probably uncontrollable aircraft in the hands of potentially unaware pilots" [p 5].

Human operators, including ATCOs, are therefore a critical feature of a gracefully degrading system, and it is essential to consider the role of the human operator in technological and automation design, as well as the design of the wider human-machine system. In the given example, the design may create challenges for the human to recover a degraded system. This in turn creates a brittle system, without the chance of online recovery. By designing systems so that the ATCO can support and potentially recover the system in a degradation event, graceful degradation can be designed into the ATM system. It is therefore essential that further research is conducted, investigating the contribution of ATCOs to both the risks of system degradation, and prevention and recovery mechanisms. Further research must be completed on both the ATCO role in relation to the newly designed automated technologies, and the interaction between the human and the wider TBO system in order to establish and validate the safety of the system. "The culmination of complex systems and humans is the greatest challenge to contend with" [19, p4516] and one that must be considered for TBO to be able to degrade gracefully. As ATCOs are at the sharp end of the safety critical ATM system, particular attention is given to the role of ground-based air traffic controllers in a gracefully degrading TBO environment for the remainder of this paper.

V. An Initial Framework of Graceful Degradation

During the literature search of articles relating to graceful degradation, it became apparent that the research could be categorized into qualitatively different facets of graceful degradation. Graceful degradation is an output of a variety of interacting factors and identification of these categories can provide deeper insight into the construction and achievement of graceful degradation in complex systems. The framework depicted in Fig. 1 aims to capture the key components of graceful degradation, and the elements that can make a system gracefully degrade.

The framework is not intended to be exhaustive, and relationships between factors are not shown due to the complex interactions between each of the elements. Where a contribution to understanding graceful degradation can be made, relationships between each facet are discussed in the following sections. The authors also acknowledge that there is not (necessarily) a linear flow between each element, although there is a temporal nature to the framework, in that a degradation must occur before identification and recovery. However, mechanisms to prevent degradation can be put in place prior to degradation occurring. There is no meaning to the length or position of lines depicted in Fig. 1, which instead simply to show the breakdown of subcategories within the overarching facet of graceful degradation. In addition, there are no directional arrows placed on the lines to avoid the presentation of directional relationship or linear temporal flow.

The framework is used to structure the remaining sections of this literature review. The aims of structuring the literature review in this way are to identify the components that have the potential to cause graceful degradation in a complex system, and identify gaps in research or understanding in the various facets of graceful degradation. By summarizing the research to date on graceful degradation in this way, findings can be applied to gain a greater insight into creating resilience and graceful degradation in a TBO environment.

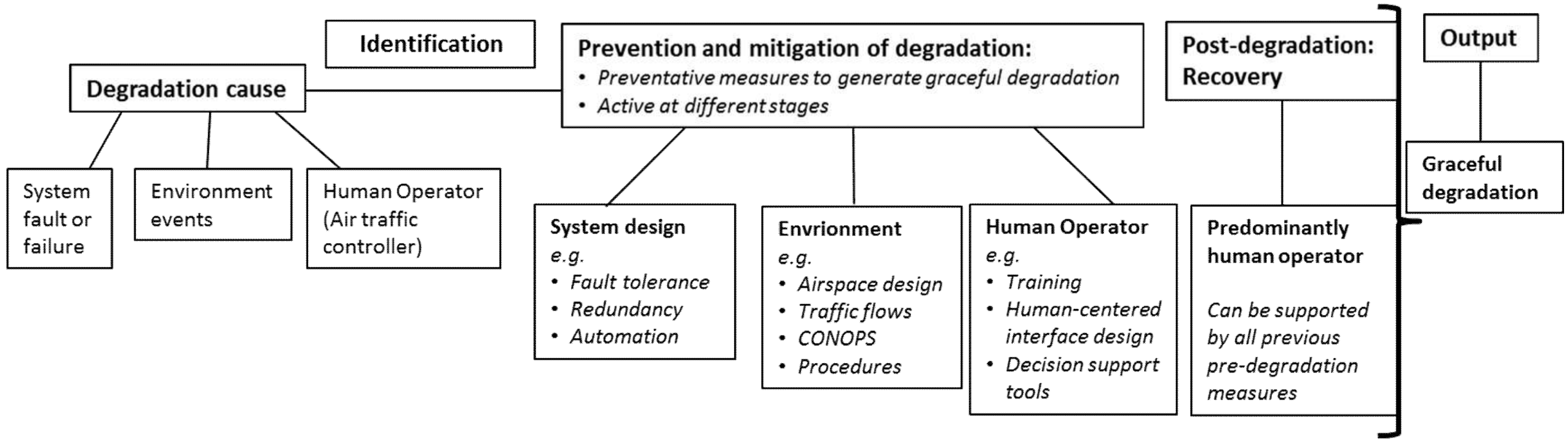

Figure 1. Framework of graceful degradation developed from the literature.

A. Framework Overview

It became apparent in the literature that there are multiple causes of system degradation, which can be divided into at least three different categories. The most dominant and frequently investigated cause is technological system failure or fault that can originate from a specific algorithm to a system wide issue, resulting in different severities of degradation. Although technological failures dominate the degradation research, other research exists that highlights environmental causes of degradation, such as off-nominal and emergency events. Degradation can also occur due to human operators. ATC operations that push ATCOs towards the edge of performance limits can potentially degrade the overall performance and safety of the system.

There is also the potential for interaction between two or all of these categories [6]. Each subcategory may act independently, or trigger another source of degradation. For example, the interaction could result from the design of the human-machine interface. If an ATCO cannot understand the automation directive, or if human decisions contracted those of the automation, then it could create unexpected complex situations that were not anticipated by either the human operators or automation designers, resulting in system degradation [6]. Another example is an off nominal event during a complex traffic scenario that could exceed the ATCO's ability handle the situation, which in turn triggers human performance degradation.

When a system has a potential for degradation, it is important that it is possible to identify a degraded state in order for mitigation mechanisms or recovery mechanisms to be actioned. Once identified, there are several solutions to address degradation documented in the literature. Solutions can broadly be divided into degradation prevention and mitigation and post-degradation recovery. Degradation prevention focuses on preemptive measures which are designed to identify and monitor the system state prior to a system degradation, to prevent degradation or mitigate the impact of degradations. Post-degradation recovery describes potential solutions designed to limit degradation and support recovery and maintenance of safe operations after degradation occurs. The most dominant sub-categories of research relating to degradation prevention are technology-based solutions, environmental solutions, and human solutions. Post-degradation, there are fewer options to assist with a gracefully degrading system. The majority of research for recovery focuses on the ability of the human operator to recover a degraded system. Some systems-focused solutions are available but often with major impacts to an operation. Together, these factors can combine to create a system that is capable of graceful degradation.

The following section describes examples of specific causes of degradation that were collected from the literature. These descriptions are not intended to be comprehensive, but instead, provide an overview of the frequently researched topics of degradation in the literature. The aims of the following section are two-fold. The first aim is to identify and summarize the potential causes of degradation that may occur in a TBO environment, and the second is to identify appropriate mitigations, ultimately contributing to knowledge that may support the development of graceful degradation within TBO.

VI. Causes of Degradation

A. Technological System Fault or Failure

The causes of ATC technological failure have received a dominant focus in the literature. The provision of ATC is dependent on a complex system of interconnected technologies, commonly divided into communication, navigation and surveillance provisions [e.g. 24]. Technological degradation, from specific algorithms to full technological system failure, can have severe consequences for safety and efficiency [19, 25, 26]. It is therefore essential to understand the potential causes of degradation in order to design appropriate mitigations [27]. Several categorizations of the causes of technological degradation have been documented in the literature (e.g. [14, 28]) although there does not appear to be a consistent methodology for identifying and categorizing causes of technological degradation and failure modes [14]. The following subsections present some of the most widely researched causes of technological degradation, categorized broadly into hardware and software in the ATC system.

1. *Causes of Hardware Failure*

Hardware failure can result in degradation. Hardware can fail for many reasons, including physical damage, aging (e.g. [29]), and accidental or malicious interference (e.g. intent to create degradation). For example, in 2007, a truck collided with a phone line pole, shutting down communications in Memphis ATC center. Approximately 200 aircraft were documented to be in the airspace at the time. With no local emergency procedure available, ATCOs utilized their personal cell phones in order to maintain a safe and efficient service [24]. This example not only highlights the potential impact of hardware failure, but also the importance of provisions for graceful degradation of the ATC system. In this case, the ATCOs recovered the situation through an ad-hoc resolution.

2. *Causes of Software Failure*

Modelling errors can be a cause of degradation in an ATC system [12, 30]. This is especially relevant in a trajectory based environment which assumes more precise aircraft trajectories for efficient traffic management. Errors in aircraft weight predictions, aircraft performance models, thrust settings, and wind predictions can all result in errors in trajectory predictions [12], which can ultimately lead to aircraft deviating from their predicted trajectories [30]. [12] provide the following illustration of the potential impact of such modelling errors: “For example, a 10% error in weight for an MD82 aircraft causes a 3-mile (25 sec) error in predicted top of descent; a 10% increase in weight (relative to nominal) for a climbing MD82 causes the aircraft to reach its top of climb 16 nautical miles later” [p6]. The impact of such modelling errors then need to be mitigated or recovered by the human operators. In an environment of interconnected technologies such as those envisaged to enable TBO, these effects this can have a cascading impact throughout the ATC technological system, influencing delays, and at worst, effecting safety [25].

Post-hoc integration of independent ATC software can also create risk of degradation. Increasingly advanced technologies are implemented through integration with legacy technologies which can often have conflicting architectures and goals [13]. An additional issue that can lead to degradation is simply the integration of different software architecture with independent, and possibly incompatible, goals [13]. [19] highlights the Uberlingen midair collision in 2002 as a disastrous consequence, in part, of the integration of automation with conflicting methods of advisories and goal achievement. Specific to TBO, trajectories calculated using different algorithms by different tools can lead to conflicting advisories based on the method of calculation and the elements considered in the algorithms which can create a “significant impact on the performance of ATM automation and hence the ATM system” [26, p3]. Presentation of conflicting advisories to ATCOs [13] can then create further confusion and complexity for the controller, with potential implications for increased workload and performance degradation.

B. Off-nominal Events and Other Environmental Factors

ATC is a dynamic environment. Unplanned and rapidly changing circumstances can potentially create degradation, if not mitigated or recovered sufficiently. With a complex system of interconnected technologies, the impact of off-nominal events can be even greater due to the potential rapid and widespread escalation through interdependent technological systems, and a decrease in flexibility to respond to unplanned events [27]. The following section summarizes some of the most frequently documented causes that could result in degradation in TBO systems.

1. *Off-nominal Events*

Off-nominal events include aircraft emergencies, medical emergencies, unexpected pilot actions (e.g. turns or level busts) [5]. Each can have a significant impact on the accuracy of trajectories and the resulting required changes to the trajectories. Depending on the situation, it is likely that the task demand for ATCOs will be increased, by manually recovering the situation in order to maintain safe and efficient operations. With the predicted increases in traffic in a TBO environment, made possible by supporting automation, the potential that ATCOs will be required to manually recover and maintain operational safety poses a significant risk to potential system degradation, with potential consequences not only for the efficiency of operations but also safety.

2. *Weather*

Weather is a much-researched area that has a large impact on ATM [19]. Weather is the leading cause of aircraft delay [12], costing billions of dollars to both airlines and passengers [31]. Convective weather is reported to account for 60% of weather-related aircraft delay [12]. Although weather avoidance routes are preplanned, real time updates are limited [12] and “there is an urgent need for automation tools…that reduce the expected delay in the air traffic control system” [31, p1].

Weather uncertainties can significantly impact TBO, with potential consequences that include manual vectoring and rerouting, delay, cancellations and trajectory prediction inaccuracies. As with the off-nominal events, these potential outcomes can have negative consequences for the ATC system, not only in terms of delay, but also for ATCOs. Demand may increase to an extent to which the human operator (ATCO) will not be able to safely mitigate the effects, or recover the system. In these cases, the whole ATC system is at significant risk for non-graceful degradation.

3. *Imprecision*

Although off-nominal events and weather can cause significant disturbances to TBO, uncertainties and imprecision in day-to-day ATC can also accumulate over time to trigger degraded operations. For example, normal departure schedule conformance can often be poor and departure time uncertainty has been documented to be a critical factor in causing uncertainty in sector demand, which has especially significant consequences for TBO [32]. In TBO, precision in aircraft meeting time windows is essential to the maintenance of operations. Imprecision and uncertainties in takeoff or landing time may result in reduced efficiency and increased delays, which might be acceptable in nominal situations, but accumulated delays under certain traffic conditions could trigger airborne holding, ground stops, or other drastic measures that could have NAS-wide consequences and rapidly degrade TBO.

4. *Airspace and Procedure Design*

The airspace design may not cause degradation in itself. In general, airspace and associated procedures are developed for safe and efficient ATC operations. However, when an event, such as technological system failure, off-nominal event or human error, triggers degradation, ill-designed or complex airspace and/or procedures may accelerate the system degradation than less complex ones. Number and type of conflict points, size of available airspace for maneuvering, military airspace activation, can all increase overall complexity which technologies must adequately take into account. In addition, airspace complexity increases ATCO demand. If the demand exceeds an ATCO's capacity, performance may be negatively affected, potentially resulting in wider system degradation [33].

C. Human Performance-influencing Factors in ATC

ATCOs are responsible for the safety of all air traffic. Because they operate at the sharp end, ATCOs can unwittingly contribute to system degradation, for example through human error. This is somewhat of a misnomer however, highlighted by so-called 'Swiss Cheese' and Resilience Engineering models [34, 35] in which there are often not one cause but several factors that can contribute to human error and system degradation.

Degraded human performance, including increases in human errors, can contribute to system degradation through several mechanisms. The following section summarizes some representative topics identified in the literature relating to the potential for ATCOs to contribute to the triggers of system degradation.

1. *Task demand and High Workload*

A large body of research from incident reports and ATC simulations has identified a negative association between high workload and ATCO performance (e.g. [36, 37]. [37] conducted a frequency analysis of ATCO errors in incident reports contained in the NASA Aviation Safety Reporting System (ASRS). Errors such as monitoring failures and incorrect heading or altitude assignments were associated with increases in taskload factors such as traffic volume. These results suggest that high workload, or possibly overloads, may be associated with degradation of ATCO performance and under extreme cases, result in performance breakdown. For example, [38] found that in certain situations under high taskloads, ATCOs used a compensation strategy to reduce the time attending to each aircraft, which in turn may have contributed to controlling errors. If the automation degrades or fails in a TBO environment, the task demand may exceed the ATCOs' ability to handle traffic safely and therefore result in errors that put the ATC system at risk of a 'cliff edge' decline as opposed to a graceful degradation. It is therefore essential that even under degraded conditions, workload still remain manageable for the ATCOs.

2. *Attention and Perceptual Errors*

Cognitive biases may cause breakdowns in selective attention [39], potentially resulting in a performance decline. One example of this is expectation-driven processing. It has been suggested in the literature that expectation driven processing allows for selective attending and perception of expected events with reduced effort compared to unfamiliar events. However, this can lead to perceptual errors such as incorrect read backs, and lack of detection in the hear-back process. Breakdowns in the visual scanning process may also occur, potentially leading to the ATCO missing critical events. [36] conducted an analysis of 48 aircraft proximity reports from three UK centers. ATCOs were recorded to have caused or contributed to the incident. Errors of perception and visual detection (no detection and late detection) in both visual and auditory modalities were the largest category of errors identified. These vigilance errors had serious implications for safety, and it can be stated with some confidence that declines of vigilance and errors of perception can result in potentially fatal consequences. This potential for degradation must be considered in a TBO environment, where potentially greater performance metric demands (such as aircraft meeting time windows) and time pressure may be placed on ATCOs [19].

3. *Communication*

Errors of communication have been repeatedly found to influence operator performance negatively, occasionally with severe consequences. Findings generally suggest that verbal and written communication errors have been a "critical contributor to risk in a variety of industries" [40, p57]. General figures suggest 40% - 80% of incidents in safety-critical domains may result from communication errors [41, 42]. [40] suggest that failures of communication may be defined by three primary criteria: the adequacy of the transfer of communication goals, deviations from accepted or regulated grammar, and errors of commission or omission when compared to contextual objectives or requirements. The Seattle center (as reported in [43]) conducted an analysis of 389 hear back/read back errors recorded during one month in 1995. Errors consisting of incorrect altitude read backs (31% of errors), incorrect radio frequency changes (24% of errors) and addressing the wrong aircraft (10%) accounted for the majority of errors. The error of communications in one month (389) suggests the pervasiveness of the communication issues and potential implications on performance. Further research must be completed to understand the communication risks with increased use of datalink, as envisaged in a TBO environment.

4. *Procedural Error*

To facilitate the management of air traffic, ATCOs must follow a series of regulations and standard procedures. However, procedures may not always be followed, either due to deliberate violation (but not malicious), slips and lapses, or a lack of procedural clarity or completeness [24]. Violation occurs when there is (non-malicious) intent to control contrary to the written procedure. This may occur for several reasons, including that a procedure may be inadequate for the operation, or judged to negatively affect efficiency. ATCOs may also not follow procedures correctly due to slips or lapses, such as forgetting a procedure or procedural change [36]. Finally, a lack of clarity which creates confusion can result in ATCOs incorrectly implementing the procedure. Failing to follow procedure can contribute to ATC incidents (e.g. [44]) and accidents [45]. Considering the potential consequences of not following procedure, it is worth noting that the new procedures required for TBO, both working practices and emergency procedures, must be thoroughly validated and tested prior to operational implementation.

D. Human-Automation Interaction

Although the previous sections have outlined the categories of causes of degradation independently, system degradation can also occur as a result of the interaction between these causes. The following sections discuss system degradation as a result of interaction between each system component.

1. *Performance-influencing Factors Resulting from Interaction with Automation*

In the human factors literature, human performance issues that result directly from increased automation have been identified. These are potentially relevant to the TBO environment in which increases in automation are predicted.

Underload

Underload has been reported to be negatively associated with ATCO performance in the literature. In a review of ATCO operational errors, [46] found that errors occurred more frequently under low or moderate workload conditions, compared to high workload (note: not overload). In addition, [47] conducted an analysis of 301 incident reports and reported that operating irregularities most frequently occurred during conditions of normal complexity and low or moderate workload. This has implications for a TBO environment, as it has been predicted that "a huge portion of the ATCO's role will be replaced by automation" [19, p4518], creating concerns of potential underload.

Trust

Trust in technology is essential to system performance in ATC [48]. In this context, trust refers to confidence in the equipment and the dependability of information. In order to be effective, it is essential that new technology and tools are accepted and used by ATCOs [49, 50] which has implications for the introduction of TBO technology enablers. Factors influencing the development of trust in technology have been reported to include ease of use as well as proof of reliability and usefulness [48]. Trust in technology is believed to influence performance through 'miscalibration' [39, 51]. When an unfamiliar technology is used, calibration is said to occur between operators and the technology/automation. This process incorporates the operator understanding when it is appropriate to trust or not trust the technology [39, 48]. A miscalibration between the operator and technology can result in mistrust or over-trust, each with specific implications for performance. Inappropriate mistrust may result in an inappropriate lack of technology use, potentially resulting in reduced efficiency or even a reduction in safe performance [39]. The concept of over-trust in aviation has been more frequently investigated in relation to automation. Over-trust of technology can result in complacency or overreliance on the technology, which has been reported to be negatively related to vigilance and monitoring behavior [52]. Data from incident reports also suggest an association between over-trust and overreliance in technology and performance decline as well as performance-related incidents. For example, in an analysis of ASRS incident reports, monitoring failures were associated with overreliance on automation [53].

2. *New Allocation of Roles and Responsibilities between Humans and Machines in a TBO environment*

The advanced automation that will enable TBO will also bring changes to the role of both the ATC technologies and ATCOs. It has been predicted that the ATCO's role will change to a more collaborative role with automation to manage safe and efficient operations (e.g. [6, 19]). There is a general acknowledgement of the importance of future human-automation collaboration in the literature. However, actual facilitators of human-automation collaboration, including role definition and method of transferring authority, are still largely under researched. Shifting authority between the agents, such as trajectory generation by the automation and approval by the ATCO, must be fully researched and communicated effectively in order to avoid integration errors and subsequent ATC system degradation. In order to maintain human performance while interacting with the automation, human-centered design is critical to prevent human error and performance declines. Issues including automation transparency and reliability (e.g. [54]) are key concerns. In addition, usability of the automation must be considered in the design stage to reduce the likelihood of confusion and ultimately human error [6].

3. *A Note on Tightly Coupled Systems*

The previous sections have provided an overview of three categories of potential causes of degradation that are relevant to TBO. Each of these causes has the potential to negatively impact the provision of safe and efficient air traffic operations. However, as NextGen and TBO necessitate moving toward increasing reliance on integrated, multiple technological systems [9] the extent of system coupling is an important area of consideration, which can directly dictate both the likelihood of degradation and the brittleness or ability of graceful degradation of the wider ATC system.

Interdependence between ATC technological systems creates increased likelihood of a more rapid and severe degradation, with less likelihood of recovery. [55] defines systems having high interdependence as 'tightly coupled' systems, with one system element linking to many others. Depending on how tightly or 'loosely' coupled a system is can influence the effect of degradation on the system, and the severity of the consequences. Tightly coupled systems have less ability to absorb failures or unplanned events without degradation. "The cascading of effects can quickly spiral out of control before operators are able to understand the situation and perform appropriate corrective actions" [56, p2], resulting in any system degradation being harder to control or resolve. [27] characterizes this concern as the 'planning vs flexibility paradox'. "A system which has been carefully planned, standardized and automated is unable to respond to nonstandard and unplanned events such as technical failures" (p1). The decrease in flexibility to respond to unplanned events has a negative impact on the potential of recovery, and in addition, increases sensitivity and reactivity and seriousness of the impact of the degradation cause and rapid degradation itself.

VII. Identification of Degradation

Identification of potential or actual degradation is required as a prerequisite for prevention, mitigation or recovery. The literature regarding identification is largely limited to degradation of automation and technological systems. Literature on identification of environmental triggers, and especially human operator degradation, is scarce.

Identification techniques can largely be separated into those that are applied to identify potential causes of degradation prior to implementation, with the aim of changing the underlying operations to prevent and mitigate degradation in future events, and techniques which are applied in real-time with the aim to prevent or recover from degradation during live operations.

Pre-implementation identification methods include incident and accident report analysis and causal modelling. Incident report analyses have been used extensively to identify and mitigate potential safety risks in ATC [15]. However, limitations exist with using retrospective data, such as the potential for a lack of personal disclosure from the operators involved, or reporting biases [15, 57]. An additional technique is causal modelling. Causal modelling can be applied through various methodologies with the aim of identifying and, depending on the model, quantifying, risk, which are then addressed with solutions that mitigate risk. Several examples of the applications of these models are documented in the literature, such as TRACEr [58] and the bow-tie methodology [59, 60].

However, in line with [61], complex systems and interactions can result in degradation that cannot be pre-identified. Therefore, it is essential that during live operations, system degradation is identified and mitigated prior to affecting other interdependent systems. As the majority of degradation identification literature relates to degradation of automation, the dominant solution space literature relates to technology which enables self-detection of degradation and an automatic fix. If the technology cannot resolve the identified issues, it is then essential that the software or hardware communicate the issue effectively to the relevant human operator. If the degradation isn't detected quickly enough, or at all, or the message to the relevant operator is not shown or unclear, degradation cannot be mitigated.

Identification of environmental triggers of degradation, or off-nominal events, is comparatively under-reported in the literature. In general, human operators, such as ATCOs, supervisors, traffic managers, must identify potential triggers for degradation and subsequently decide on resolutions. For some environmental causes, tools can support this decision, such as weather prediction tools or sector demand prediction tools. However, a critical issue is timing – if an operator can identify an off-nominal situation to allow for planning time, such as in the case of weather, then mitigations can be implemented with minimal impact on the operation. Sudden changes without early identification, such as aircraft emergencies, may create a larger risk of degradation, especially in highly precise and tightly coupled systems with high numbers of aircraft.

Identification of performance degradation in human operators is especially under-represented in the literature. Although there is some initial work on identifying markers of performance degradation during live operations [62] this area requires significant further research.

VIII. Prevention and Mitigation Methods for Graceful Degradation

Solutions to system degradation are reported in the literature, although overall, research on solutions is more sporadic and less frequent compared to research on the causes of degradation. A broad distinction can be made between solutions that are applied prior to implementation of a new technology that aim to prevent degradation causes, solutions that are applied during live operations that aim to predict and prevent or mitigate a degradation cause (e.g. traffic load prediction, whether tools), and solutions applied during operation but after degradation has occurred, with the aim to mitigate degradation and recover the ATC system to maintain safe operations. The majority of the solutions presented in the literature are applied 'offline' (i.e. not during operations), and aim to prevent degradation from occurring through redesign of the technology and the wider system. Through future research, more solutions can be applied in real time, such as the increasing focus on research relating to real time safety modeling [63].

The following section provides an overview of selected solutions to specific causes of degradation that have been identified in the literature, separated into solutions that are applied to prevent and mitigate degradation, and solutions that are applied post-degradation to recover the system. In keeping with the structure used to present the causes of degradation, the solutions will be presented in relation to the broad categorizations of technology solutions, environmental solutions, and mitigation strategies by the human operator.

A. Technological System-related Solutions

Technological system-related techniques for the prevention of degradation are numerous, and well documented in the literature. [18] reports a list of preventative solutions and mitigations for technological vulnerabilities. Of the 18 identified mitigations, 14 were related to technology design and regulation (Table 1). Table 1 provides an excellent summary of the main techniques utilized to prevent degradation, or ensure graceful degradation.

1a.Integrity Limits	Limits, specified by design, to ensure performance never falls below initial requirements throughout the life of the system or component.
1b.Quality Standards	Standards, specified by design, to ensure satisfactory performance of systems and components at the time of delivery into the meta-system.
2a. Redundancy	Additional components or systems that provide continuous uninterrupted functionality at the same level of performance (but not necessarily efficiency) after any single (or other defined number of) failure(s); e.g., two or more engines, hydraulic systems, flight control systems, etc.

2b.Backup Systems	Additional components or systems that provide replacement at potentially lower levels of performance after failure of the primary system(s) that provide the function; e.g., radar as a backup to ADS-B.
3. Isolation	Physical, electrical, data/informational, and social distancing and/or segregation of systems, components, and elements so the failure of one does not cause the failure of another.
4a.Proven Reliability Levels	Specification of performance levels for systems, components, and elements so a condition of coincidentally occurring, independent failures is unforeseeable. This is to ensure continued functionality of dependent components and continuous availability of the system to respond to failures; e.g. include software Development Assurance Levels (DALs) and demonstrated service life in equivalent environments.
4b.Verification & Validation	New or improved independent procedures used together for checking that a product, service, or system meets requirements and specifications, and that it safely fulfills its intended purpose.
5. Failure Warning or Indication	Features that provide detection and enunciation of system abnormalities. This includes internal monitoring: the functions added to a system or component for error checking, status and performance monitoring, and other means for self-checking its condition and outputs.
6a. Procedures	Requirements for automation and human intervention specifying corrective action for use after failure (including exceedance of limits).
6b. Training	The acquisition of knowledge, skills, and competencies in order to improve an individual's or a team's capability, capacity, and performance to a minimum standard.
7a. Checkability	The capability and procedures [human in the loop (HITL)] for humans or automation to check a system or component's condition and outputs.
7b.External Monitor	An independent system or component (but not a human procedure) that provides error checking, status and performance monitoring, and other means for monitoring a system or component's condition and outputs; e.g. health monitoring or fast-time predictive analysis.
8a.Failure Effect Limits	Design features and characteristics, including the capability to sustain damage, that limit the safety impact or effects of a failure.
8b. Failure Paths	Design attributes that control and direct the effects of a failure in a prescribed way that limits its safety impact.
9a.Error-Tolerance	Features to mitigate the adverse effects of errors foreseen during the system's design, test, manufacture, operation, and maintenance.
9b.Requirements Engineering	A formal, organized process for ensuring adequate and complete requirements definition. This includes all of the activities involved in discovering, documenting and maintaining a set of requirements for a complex system.
10a.Buffers, Margins or Factors of Safety:	Buffers, margins or factors of safety applied to the infrastructure of the system to allow for any undefined or unforeseeable adverse conditions without performance penalties.
10b.Performance Governors	Buffers, margins and factors of safety applied to the performance parameters of the system to manage and regulate its operation to below levels prescribed as unsafe.
11. Retire by Design	To choose a design that is inherently insusceptible to the given vulnerability.

Table 1. Mitigations for complex systems. Replicated from [18].

As can be seen from Table 1, a division can be made between hardware solutions, software solutions and requirement-based mitigations. Physical safeguards include external monitoring, failure effect limits, and redundancy. [8] provides further detail, reporting that the industry practice for dealing with faults and failures is fault tolerance and fault containment. [64] further contribute to this list, identifying 24 principles of safety engineering, divided into the categories of inherently safe design, safety reserves, safe-fail and procedural safeguard's (see [64], for more detail). [18] also identified non-technical preventative measures for technological causes of degradation. For example, verification and validation prior to operational use could highlight potential issues. In addition, routine physical checks of the machinery, risk analysis, and implementation of quality standards, prior to implementation can also be utilized effectively to identify and prevent technological causes of degradation.

B. Environmental Solutions for Causes of Degradation

Environmental solutions to degradation often focus on reducing complexity for the human operators, or increasing the available time and capacity to enable human operators to maintain safe operations in a degraded state. For example, traffic flows could be rearranged prior to implementation of new technologies and automation such as those that enable TBO to reduce the overall demand or complexity (e.g. put aircraft in sequence with matching speeds) to both increase safety buffers and reduce ATCO workload during the degraded state.

Airspace redesign can prevent and mitigate degradation both directly and indirectly. Directly, redesign of airspace characteristics can create backup options to maintain safe operations during degradation. For example, creating standard aircraft flows in association with the miles in trail control strategy results in aircraft maintaining safe separation with minimal inputs or dependency on technology such as communications. In the case of a technology failure, the aircraft will remain safely separated, minimizing the impact of the degradation. Airspace design can also support graceful degradation through supporting the human operator in maintaining safe operations to recover the degraded system. [65] proposed that the use of flexible airspace and replacement of holding patterns will allow for more efficient re-routes or aircraft holding for high density traffic in off-nominal events, again creating capacity and time for the human operators to recover the situation. In addition, reducing airspace complexity may also support graceful degradation. Airspace complexity can directly affect human performance of pilots and ATCOs, potentially resulting in error. Airspace complexity also creates demand on ATCOs, which may also negatively impact performance. [66] used field observations and interviews of ATCOs to generate a list of complexity factors. The underlying structure of the airspace was one of the most frequently identified issues. By redesigning airspace to reduce complexity, human errors are less likely. In addition, ATCOs have more capacity to prevent and recover a degrading system.

Environmental mechanisms to prevent degradation are also used in ATC. Examples of these solutions include the creation and validation of a clear CONOPs supports ATCOs in fulfilling duties in line with expectations, clear emergency procedures support ATCOs in recovering off-nominal situations and maintain safe operations, training ATCOs in new technologies and emergency procedures reduce the likelihood of human error.

C. Degradation Mitigation Strategies by the Human Operators

Literature relating to the explicit contribution of human operators, and specifically ATCOs, to graceful degradation is relatively under-researched compared to the areas of technological system design and environment-based solutions. Offline solutions include research around training methods for human operators, which assume that ATCOs can provide a constant contribution to preventing system degradation with the ability to maintain a consistently high standard of human performance [19].

During operations, operators also work with automation to prevent or mitigate degradation caused by the environment or human operators. For example, tools such as enhanced weather prediction can prevent and mitigate potential environmental causes of degradation such as unexpected weather characteristics. However, in order for these technological solutions to be effective in preventing triggers of degradation, it is essential that the technology utilizes human-centered design principles. Automation design issues must be fully considered, including automation visibility, accuracy, and usability principles [6].

However, there is little research regarding the detection and prevention of ATCO's reaching performance limits, and potential degradation of human performance. Some foundational research has investigated the concept of a 'Human Performance Envelope Model' [15, 67]. The notion of an 'envelope model' enables modeling of the interactions between human factor influences on performance, such as workload and fatigue, and the interaction between these factors and the subsequent collective influence on performance. In addition, the human performance envelope paradigm suggests that there are ‘edges’ of performance and that performance may reach a specific limit or boundary after which a decline in performance may occur [62]. By utilizing the concept of a performance envelope, through future research it may be possible to predict when ATCO performance degradation is most likely (in relation to human factor influences such as workload, fatigue, and stress) and implement supportive strategies prior to a performance decline or degradation. In addition, by expanding and applying research on the indicators that controllers are reaching limits of performance, it may be possible to identify when ATCOs are reaching a performance degradation point *during* operations, therefore enabling preventative mechanisms to be applied to prevent performance decline and potential wider system degradation.

IX. Post-degradation Recovery Mechanisms

A large contribution of ATCOs to achieving graceful degradation is maintenance of safe operations in the face of technical faults and failures or environmental off-nominal events. The reliance on the ATCO during emergencies is demonstrated by the ICAO 4444 document which specifies emergency procedures for ATCOs in a wide variety of degraded conditions. The role of the ATCO as the on-line defense between safe operations and unsafe, degraded operations in current day ATC is critical to consider in a future TBO environment. One of the goals of TBO is to enable increases in airspace capacity. Therefore, ATCOs could be controlling a number of aircraft that, without automation, they would not have the capacity to control safely. Therefore, if the automation fails or degrades and the role of the ATCO is still assumed to be to maintain safe operations and recover the degraded system, there is significant risk that recovery cannot be made, resulting in unsafe operations. Therefore, the design of TBO must consider the extent that the ATCO should contribute to a graceful degradation of the system should technological or environmental triggers of degradation occur, and provide mechanisms to support the ATCO as needed. Such mechanisms may include restriction of the number of aircraft to within tolerable limits of safe control for the ATCO, adequate time and capacity for degradation recovery, and support tools that enable early identification of potential degradation.

X. Output - Achieving Graceful Degradation in TBO

A. Need for Human-machine System Integration

TBO marks a fundamental change in air traffic management. Technological and automation advancements will create change in the provision of traffic management, moving from manual and tactical control to automated and strategic control. The role of the ATCO will change, and ATCOs will be responsible for more aircraft than could be safely controlled without automation. If ATCOs are routinely operating outside of what they can control safely without automation, the TBO system will be at risk of being brittle. If the automation fails, ATCOs would not be able to control air traffic reliably or safely. As a result, without a reliable recovery opportunity, graceful degradation will be nearly impossible to achieve during live operations.

In the TBO environment, graceful degradation can only be achieved through collaboration between the human operator (ATCO) and the technological systems. An example concept of such collaboration includes both human and technological system operating as the backup for each other in degraded operations. For example, with the occurrence of technological degradation, the TBO environment must be designed so that the operator can effectively and safely continue to control air traffic with a degraded system. In addition, an ATCO will require advanced automation in order to control traffic efficiently and safely in TBO operations. In order to achieve a TBO ATM system that is capable of graceful degradation, it is necessary to ensure that both the human ATCO and the system are available and have the capacity for recovery in case of fault or failure. Traditionally, graceful degradation has been viewed in terms of degradation of the automation system and the recovery into a degraded state by human operators. In the ATC environment, we should expand the scope of the research to include potential degradation of the system, environment, and human operators and potential changes to all three to either prevent or recover from the degraded state. In such an environment, it is critical to examine the human-system integration in the context of a realistic environment. There is a current gap in research on how to achieve such a collaborative system in TBO, which will ultimately lead to designing graceful degradation into the TBO environment.

XI. Discussion and Conclusion

This literature review aimed to summarize the research to date on the most frequently researched causes of ATM related system degradation, and associated solutions of degradation, that were applicable to the TBO environment. An additional aim was to identify the role of the human operator, specifically, ground-based air traffic ATCOs in a gracefully degrading system. Finally, the review aimed to develop a summary framework of graceful degradation based on the available literature. The framework encompasses the potential impact of technology or human operator breakdown, as well as the complexity of the air traffic environment at the time of the breakdown, and categorizes them into different phases of detection and recovery. The ultimate aim of the framework is to develop research questions and design solutions to develop resilient TBO systems and procedures using a holistic view of human-machine system integration.

Causes of degradation in ATC were identified and summarized, contributing to the first aim. Findings revealed that causes of degradation identified in the literature could be broadly categorized into those resulting from technological systems, the environment, or human operators. It was also identified that the impact of the causes of degradation that occur in current day ATC operations may be exacerbated in TBO operations by the necessary increases in precision and tightly coupled systems. Identification of the risks of potential degradation, and identifying actual degradation during live operations, was highlighted as a key aspect in creating a gracefully degrading system. The most relevant techniques to identifying degradation in an ATM system were summarized. Finally, solutions to address degradation were identified. Solutions were again broadly categorized into technical, environmental and human operator-related solutions. It was found that solutions could be further subcategorized into offline techniques, which aimed to prevent the causes of degradation, or techniques for use in live operations, which were designed to mitigate the impact of degradation and recover safe operations, therefore achieving graceful degradation. Together, these findings achieved the first and third aims of the review, and provide further infight into the risk of degradation in a TBO environment, and potential solutions to address the degradation.

It was identified that the majority of previous research has focused on understanding system and technological-related causes of degradation. A gap in understanding was identified in the literature regarding the contribution of human operators, and specifically, air traffic ATCOs, to both the contribution to the potential causes of degradation and creation of a gracefully degrading system. Research was sparse on the role of ATCOs in a gracefully degrading system, although of the articles that did consider the ATCO, a majority made an implicit assumption that the role of the ATCO was to recover a degrading system, such as from weather influences on traffic, aircraft emergencies, and failures or faults in software and hardware, achieving the second aim of the review. The assumption that the ATCO will support safe operations during technological failure assumption, if carried through to the TBO concept, has specific implications for the design of TBO. The technology that enables TBO makes it possible for ATCOs to manage more aircraft than they could manage manually, without automation. If the technology fails, the ATCO may not be able to safely recover and maintain operations. A human-machine system integration approach therefore needs to be applied to achieving graceful degradation in TBO, acknowledging the role of the human operator. Further research is needed in this area in order to fully understand how degradation can occur, and how graceful degradation can be achieved, in a TBO environment. Further research must consider the role of the human operator, specifically, the ATCO, in contributing to graceful degradation in TBO. Research must also investigate the 'performance envelope' of the ATCO, and the situations under which ATCOs can, and cannot, safely recover a degraded TBO system, for example, through a reduction in complexity or required precision, whilst maintaining maximal efficiency. Further research is also required on the modification of how tightly or loosely coupled the TBO system operates, as a solution to achieving graceful degradation, both mitigating degradation and supporting recovery of safe operations. By utilizing the integrative framework presented in this paper to address the identified research gaps and develop further solutions, graceful degradation can be designed into the TBO environment to enhance system resiliency, and ultimately, safety.

Appendix
References Organized by Literature Review Category

Causes of Degradation

Technological System Fault or Failure

[12]McNally, D., Mueller, E., Thipphavong, D., Paielli, R., Cheng, J. H., Lee, C. & Walton, J., "A Near-Term Concept for Trajectory Based Operations with Air/Ground Data Link Communication". *Proceedings of 27th International Congress of the Aeronautical Sciences*, Nice, France, 2010.

[13]Cate, K. T., "Challenges in achieving trajectory-based operations". *In 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, TX, USA, 2013.

[14]Gariel, M., Feron, E., & Clarke, J. P., "Air traffic management complexity maps induced by degradation of Communication, Navigation and Surveillance," *AIAA Guidance, Navigation and Control Conference and Exhibit, 2008*, pp. 18-21

[19]Lyons, R., "Complexity analysis of the next gen air traffic management system: trajectory based Operations," *Work*, 41(Supplement 1), 2012, pp. 4514-4522

[24]Gariel, M., "Toward a graceful degradation of air traffic management systems". PhD Thesis. Georgia Institute of Technology, USA, 2010.

[25]Sheridan, T. B., "Next generation air transportation systems: Human-automation interaction and organizational risks," *Proceedings of the 2nd Symposium on Resilience Engineering* November 8th-10th, Juan-les-Pins, France, 2006, pp. 272-282

[26]Mondoloni, S., Swierstra, S., & Paglione, M., "Assessing trajectory prediction performance-metrics definition," *24th Digital Avionics Systems Conference* (Vol. 1), October, Washington, DC, USA, 2005, pp. 3-C

[27]Hollnagel, E., Martinie, C., Palanque, P., Pasquini, A., Ragosta, M., Rigaud, E., & Silvagni, S., "System Performance under Automation Degradation" (WP-E project SPAD). *First SESAR Innovation Days*, 29 November – 1 December, Toulouse, France, 2011

[28]Landry, S. J., Archer, J., & Nguyen, N., "Enumeration of National Airspace System uncertainties within an agent-based, state-based model," *AIAA Aviation Conference*. Los Angeles, CA, 2013.

[29]Klutke, G. A., & Yang, Y., "The availability of inspected systems subject to shocks and graceful Degradation," *IEEE Transactions on Reliability*, 51(3), 2002, pp. 371-374.

[30]Jackson, M. R., "Role of avionics in trajectory-based operations," *IEEE Aerospace and Electronic Systems Magazine*, 25(7), 2010, pp. 12-19.

Off-nominal Events and Other Environmental Factors

[5]Prevot, T., Homola, J., Mercer, J., Mainini, M., & Cabrall, C., "Initial evaluation of NextGen air/ground operations with ground-based automated separation assurance," *Proceedings of the 8th USA/Europe Air Traffic Management Research and Development Seminar*, CA, USA, 2009.

[12]McNally, D., Mueller, E., Thipphavong, D., Paielli, R., Cheng, J. H., Lee, C. & Walton, J., "A Near-Term Concept for Trajectory Based Operations with Air/Ground Data Link Communication". *Proceedings of 27th International Congress of the Aeronautical Sciences*, Nice, France, 2010.

[19]Lyons, R., "Complexity analysis of the next gen air traffic management system: trajectory based Operations," *Work*, 41(Supplement 1), 2012, pp. 4514-4522

[31]Nilim, A., El Ghaoui, L., Duong, V., & Hansen, M., "Trajectory-based air traffic management (TBO-ATM) under weather uncertainty," *Proceedings of the 4th USA/Europe air traffic management R&D seminar*, NM, USA, 2001.

[32]Engelland, S. A., & Capps, A., "Trajectory-Based Takeoff Time Predictions Applied to Tactical Departure Scheduling: Concept Description, System Design, and Initial Observations," *Proceedings of the 11th AIAA Aviation Technology, Integration and Operations (ATIO) Conference*, 20-22 September, Virginia Beach, VA, 2011.

[33]Wanke, C., Callaham, M. B., Greenbaum, D. P., & Masalonis, A. J., "Measuring uncertainty in airspace demand predictions for traffic flow management applications," *AIAA Guidance, Navigation and Control Conference*, TX, USA, 2003.

Human Performance-influencing Factors in ATC

[34]Hollnagel, E., Woods, D. D., & Leveson, N., *Resilience engineering: Concepts and precepts*, UK: Ashgate Publishing Company, 2006.

[35]Reason, P., & Bradbury, H. (Eds.), *Handbook of action research: The concise paperback edition*. UK: Sage Publications, 2006.

[36]Shorrock, S. T., "Errors of perception in air traffic control," *Safety Science*, 45, 2007, pp. 890-904

[37]Morrison, R., & Wright, R.H., "Air traffic control and communications problems: An overview of recent ASRS data," *Proceedings of the Fifth International Symposium on Aviation Psychology*, 1989, 902-907.
[38]Endsley, M. & Rodgers, M. D., "Attention distribution and situation awareness in air traffic control," *Proceedings of the 40th Annual Meeting of the Human Factors Society*, 1996.
[39]Wickens, C. D., Mabor, A. S., & McGee, J. P., *Flight to the Future: Human Factors in Air Traffic Control*, National Academy Press, Washington D.C., USA, 1997.
[40]Gibson, W. H., Megaw, E. D., Young, M. S., & Lowe, E., "A taxonomy of human communication errors and application to railway track maintenance," *Cognition, Technology & Work*, 8(1), 2006, 57-66.
[41]Sexton, J. B. & Helmreich, R. L., "Analyzing cockpit communication: The links between language, performance, error, and workload," *Proceedings of the Tenth International Symposium on Aviation Psychology*, Columbus, OH, 1999.
[42]Tajima, A., "Fatal miscommunication: English in aviation safety". *World Englishes*, 23(3), 2004, pp. 451-470
[43]Isaac, A. R. & Ruitenberg, *Air traffic control: Human performance factors*, UK: Ashgate publishing company. 1999.
[44]Pape, A. M., Wiegmann, D. A., & Shappell, S., "Air traffic control (ATC) related accidents and incidents: A human factors analysis," *Proceedings of the 11th International Symposium on Aviation Psychology*, Columbus, OH, The Ohio State University, 2001.
[45]Nunes, A., & Laursen, T., "Identifying the factors that contributed to the Überlingen Midair Collision," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 48, No. 1), Los Angeles, CA: SAGE Publications, 2004, pp. 195-198
[46]Redding, R. E., "Analysis of operational errors and workload in air traffic control," *Human Factors and Ergonomics Society Annual Meeting Proceedings*, 36(17), 1992, 1321-1325
[47]Stager, P., Hameluck, D., & Jubis, R., "Underlying factors in air traffic control incidents," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 33, No. 2). SAGE Publications, 1989, pp. 43-46
[48]Bonini, D., "ATC do I trust thee?: Referents of trust in air traffic control," *CHI'01 Extended Abstracts On Human Factors In Computing Systems*, ACM, 2001, pp. 449-450
[49]Eidelkind, M., & Papantonopoulos, S., "Operator trust and task delegation: Strategies in semi-autonomous agent systems," *Human-Automation Interaction: Research and Practice*, Erlbaum Associates, 1997.
[50]Muir, B. M., "Trust between humans and machines, and the design of decision aids," *International Journal of Man-Machine Studies*, 27(5-6), 1987, 527-539
[51]Wickens, C. D., "Situation awareness and workload in aviation," *Current Directions in Psychological Science*, 11(4), 2002, pp. 128-133
[52]Muir, B. M., & Moray, N., "Trust in automation: part II, experimental studies of trust and human intervention in a process control simulation," *Ergonomics*. 37(11), 1996, pp. 1905-1922
[67]Graziani, I., Berberian, B., Kirwan, B., Le Blaye, P., Napoletano, L., Rognin, L., & Silvagni, S., "Development of the Human Performance Envelope Concept for Cockpit HMI Design," *HCI-Aero 2016 International Conference on Human-Computer Interaction in Aerospace*, 2016.
[66]Histon, J. M., Hansman, R. J., Gottlieb, B., Kleinwaks, H., Yenson, S., Delahaye, D., & Puechmorel, S., "Structural considerations and cognitive complexity in air traffic control," *Digital Avionics Systems Conference* (Vol. 1) Irvine, CA, USA, 2002, pp. 1C2-1
[62]Edwards, T., Sharples, S., Kirwan, B., Wilson, J.R., "Identifying Markers of Performance Decline in Air Traffic Controllers," Di Bucchianico, G., Vallicelli, A., Stanton, N.A., Landry, S.J. (eds.) *Human Factors in Transportation: Social and Technological Evolution Across Maritime, Road, Rail, and Aviation Domains*, 2016.
[58]Shorrock, S. T., & Kirwan, B., "Development and application of a human error identification tool for air traffic control," *Applied Ergonomics*, 33(4), 2002, pp. 319-336
[59]Bellamy, L. J., Ale, B. J., Geyer, T. A. W., Goossens, L. H., Hale, A. R., Oh, J., & Whiston, J. Y., "Storybuilder—A tool for the analysis of accident reports," *Reliability Engineering & System Safety*, 92(6), 2007, pp. 735-744

Human-automation Interaction

[6]Landry, S, "Intensity Control: A Concept for Automated Separation Assurance Safety and Function Allocation in NextGen." *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2012, p. 5414
[19]Lyons, R., "Complexity analysis of the next gen air traffic management system: trajectory based Operations," *Work*, 41(Supplement 1), 2012, pp. 4514-4522
[27]Hollnagel, E., Martinie, C., Palanque, P., Pasquini, A., Ragosta, M., Rigaud, E., & Silvagni, S., "System Performance under Automation Degradation" (WP-E project SPAD). *First SESAR Innovation Days*, 29 November – 1 December, Toulouse, France, 2011
[39]Wickens, C. D., Mabor, A. S., & McGee, J. P., *Flight to the Future: Human Factors in Air Traffic Control*, National Academy Press, Washington D.C., USA, 1997.

[46]Redding, R. E., "Analysis of operational errors and workload in air traffic control," *Human Factors and Ergonomics Society Annual Meeting Proceedings*, 36(17), 1992, 1321-1325
[47]Stager, P., Hameluck, D., & Jubis, R., "Underlying factors in air traffic control incidents," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 33, No. 2). SAGE Publications, 1989, pp. 43-46
[48]Bonini, D., "ATC do I trust thee?: Referents of trust in air traffic control," *CHI'01 Extended Abstracts On Human Factors In Computing Systems*, ACM, 2001, pp. 449-450
[49]Eidelkind, M., & Papantonopoulos, S., "Operator trust and task delegation: Strategies in semi-autonomous agent systems," *Human-Automation Interaction: Research and Practice*, Erlbaum Associates, 1997.
[50]Muir, B. M., "Trust between humans and machines, and the design of decision aids," *International Journal of Man-Machine Studies*, 27(5-6), 1987, 527-539
[51]Wickens, C. D., "Situation awareness and workload in aviation," *Current Directions in Psychological Science*, 11(4), 2002, pp. 128-133
[52]Muir, B. M., & Moray, N., "Trust in automation: part II, experimental studies of trust and human intervention in a process control simulation," *Ergonomics*. 37(11), 1996, pp. 1905-1922
[53]Mosier, K. L., Skitka, L. J., & Korte, K. J., "Cognitive and social psychological issues in flight crew/automation interaction," M. Mouloua, & R. Parasuraman (Eds.), *Human performance in automated systems: Current research and trends*, Hillsdale NJ: Erlbaum, 1994
[54]Foyle, D. C., Hooey, B. L., Bakowski, D. L., Williams, J. L., & Kunkle, C. L., "Flight deck surface trajectory-based operations (STBO): Simulation results and ConOps implications," *Ninth USA/Europe Air Traffic Management Research and Development Seminar* (Paper 132), EUROCONTROL/FAA. Berlin, Germany, 2011.
[55]Perrow, C., Normal accidents. Basic Books Inc.: New York New York, USA, 1999.
[56]Marais, K., Dulac, N., & Leveson, N., "Beyond normal accidents and high reliability organizations: The need for an alternative approach to safety in complex systems," *Engineering Systems Division Symposium*, Massachusetts Institute of Technology, Cambridge, MA: MIT, 2004, pp. 29-31
[61]Rasmussen, J., "Information processing and human-machine interaction; An approach to cognitive engineering," *Series in System Science and Engineering*. Amsterdam: North Holland, 1986.

Identification of Degradation

[57]Johnson, C. W. "Reasons for the failure of incident reporting in the healthcare and rail industries". In *Components of System Safety: Proceedings of the 10th Safety-Critical Systems Symposium*. Berlin: Springer Verlag, 2002, pp. 31-60.
[58]Shorrock, S. T., & Kirwan, B., "Development and application of a human error identification tool for air traffic control," *Applied Ergonomics*, 33(4), 2002, pp. 319-336
[59]Bellamy, L. J., Ale, B. J., Geyer, T. A. W., Goossens, L. H., Hale, A. R., Oh, J., & Whiston, J. Y., "Storybuilder—A tool for the analysis of accident reports," *Reliability Engineering & System Safety*, 92(6), 2007, pp. 735-744
[60]Ale, B. J. M., Bellamy, L. J., Roelen, A. L. C., Cooke, R. M., Goossens, L. H. J., Hale, A. R., & Smith, E., "Development of a causal model for air transport safety," *ASME 2005 International Mechanical Engineering Congress and Exposition*, Kolowrocki (Ed.), Advances in Safety and Reliability, Taylor and Francis Group, London, 2005, pp. 107-116
[61]Rasmussen, J., "Information processing and human-machine interaction; An approach to cognitive engineering," *Series in System Science and Engineering*. Amsterdam: North Holland, 1986.
[62]Edwards, T., Sharples, S., Kirwan, B., Wilson, J.R., "Identifying Markers of Performance Decline in Air Traffic Controllers," Di Bucchianico, G., Vallicelli, A., Stanton, N.A., Landry, S.J. (eds.) *Human Factors in Transportation: Social and Technological Evolution Across Maritime, Road, Rail, and Aviation Domains*, 2016.
[64]Möller, N., & Hansson, S. O., "Principles of engineering safety: risk and uncertainty reduction," *Reliability Engineering & System Safety*, 93(6), 2008, 798-805

Prevention and Mitigation Methods for Graceful Degradation

Technological System-related Solutions

[8]Shelton, C. P., Koopman, P., & Nace, W., "A framework for scalable analysis and design of system-wide graceful degradation in distributed embedded systems", *Proceedings of the Eighth International Workshop on Object-Oriented Real-Time Dependable Systems*, CA, USA, 2003, pp. 156-163
[18]Bertish, S., Darr, S., Hemm, R., Swenor, P., Dickerson, N., Tejeda, J., & Gawdiak, Y., "Initial System Integrity Assessment for Safety: Methods and NGOps-4 Results". *AIAA Aviation Forum*, August 12-14, Los Angeles, CA, 2013.
[64]Möller, N., & Hansson, S. O., "Principles of engineering safety: risk and uncertainty reduction," *Reliability Engineering & System Safety*, 93(6), 2008, 798-805

Environmental Solutions for Causes of Degradation

[65]Chen, J. T., Ganji, M., Krozel, J., Kicinger, R., Yang, S., & Mitchell, J. S., "Modeling off-nominal events and mitigation strategies for super density operations," *IEEE/AIAA 31st Digital Avionics Systems Conference* (DASC),Williamsburg, Virginia, USA, 2012, pp. 3A4-1

[66]Histon, J. M., Hansman, R. J., Gottlieb, B., Kleinwaks, H., Yenson, S., Delahaye, D., & Puechmorel, S., "Structural considerations and cognitive complexity in air traffic control," *Digital Avionics Systems Conference* (Vol. 1) Irvine, CA, USA, 2002, pp. 1C2-1.

Degradation Mitigation Strategies by the Human Operators

[6]Landry, S, "Intensity Control: A Concept for Automated Separation Assurance Safety and Function Allocation in NextGen." *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2012, p. 5414

[15]Edwards, T., Sharples, S., Wilson, J. R., and Kirwan, B., "Factor interaction influences on human performance in air traffic control: The need for a multifactorial model," *Work: A Journal of Prevention, Assessment and Rehabilitation*, 41(1), 2012, pp. 159-166.

[19]Lyons, R., "Complexity analysis of the next gen air traffic management system: trajectory based Operations," *Work*, 41(Supplement 1), 2012, pp. 4514-4522

[62]Edwards, T., Sharples, S., Kirwan, B., Wilson, J.R., "Identifying Markers of Performance Decline in Air Traffic Controllers," Di Bucchianico, G., Vallicelli, A., Stanton, N.A., Landry, S.J. (eds.) *Human Factors in Transportation: Social and Technological Evolution Across Maritime, Road, Rail, and Aviation Domains*, 2016.

[67]Graziani, I., Berberian, B., Kirwan, B., Le Blaye, P., Napoletano, L., Rognin, L., & Silvagni, S., "Development of the Human Performance Envelope Concept for Cockpit HMI Design," *HCI-Aero 2016 International Conference on Human-Computer Interaction in Aerospace*, 2016.

References

[1]JPDO, "Concept of Operations for the Next Generation Air Transportation System" (Version 3.2), 2010.Washington, DC.

[2]EUROCONTROL, "Five Major Challenges of Long-term Air Traffic Growth". Published at https://www.eurocontrol.int/eec/public/standard_page/ETN_2009_1_Growth.html, 2008.

[3]SESAR Consortium, SESAR D3. "The ATM Target Concept", Document No. DLM-0612-001-02-00a, 2007.

[4] Federal aviation administration, "4D trajectory based operations (4D TBO)". Concept of operations CONOPS (version 1), 2014.

[5]Prevot, T., Homola, J., Mercer, J., Mainini, M., & Cabrall, C., "Initial evaluation of NextGen air/ground operations with ground-based automated separation assurance," *Proceedings of the 8th USA/Europe Air Traffic Management Research and Development Seminar*, CA, USA, 2009.

[6]Landry, S, "Intensity Control: A Concept for Automated Separation Assurance Safety and Function Allocation in NextGen." *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2012, p. 5414

[7]Hollnagel, E. "How resilient is your organisation? An introduction to the Resilience Analysis Grid (RAG)." In *Sustainable transformation: Building a resilient organization*. 2010.

[8]Shelton, C. P., Koopman, P., & Nace, W., "A framework for scalable analysis and design of system-wide graceful degradation in distributed embedded systems", *Proceedings of the Eighth International Workshop on Object-Oriented Real-Time Dependable Systems*, CA, USA, 2003, pp. 156-163

[9]Harkleroad, E., Vela, A., Kuchar, J., Barnett, B., & Merchant-Bennett, R., "Risk-based Modeling to Support NextGen Concept Assessment and Validation". Lincoln Laboratory, Lexington, MA, Project Report ATC-405, 2013.

[10]Rasmussen, T. & Jeppesen, H. J., "Teamwork and associated psychological factors: A review". *Work & Stress*, 20(2), 2006, pp. 105-128

[11]Hetherington, C., Flin, R. & Mearns, K., "Safety in shipping: The human element". *Journal of Safety Research*, 37, 2006, pp. 401-411

[12]McNally, D., Mueller, E., Thipphavong, D., Paielli, R., Cheng, J. H., Lee, C. & Walton, J., "A Near-Term Concept for Trajectory Based Operations with Air/Ground Data Link Communication". *Proceedings of 27th International Congress of the Aeronautical Sciences*, Nice, France, 2010.

[13]Cate, K. T., "Challenges in achieving trajectory-based operations". *In 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, TX, USA, 2013.

[14]Gariel, M., Feron, E., & Clarke, J. P., "Air traffic management complexity maps induced by degradation of Communication, Navigation and Surveillance," *AIAA Guidance, Navigation and Control Conference and Exhibit, 2008*, pp. 18-21

[15]Edwards, T., Sharples, S., Wilson, J. R., and Kirwan, B., "Factor interaction influences on human performance in air traffic control: The need for a multifactorial model," *Work: A Journal of Prevention, Assessment and Rehabilitation*, 41(1), 2012, pp. 159-166.

[16]Kirwan, B., *A guide to practical human reliability assessment*. CRC press, UK, 1994.

[17]Lin, Y., & Kulkarni, S., "Automated multi-graceful degradation: a case study", *Proceedings of the IEEE Symposium on Reliable Distributed Systems*," Braga, Portugal, 2013, pp. 81-90

[18]Bertish, S., Darr, S., Hemm, R., Swenor, P., Dickerson, N., Tejeda, J., & Gawdiak, Y., "Initial System Integrity Assessment for Safety: Methods and NGOps-4 Results". *AIAA Aviation Forum*, August 12-14, Los Angeles, CA, 2013.

[19]Lyons, R., "Complexity analysis of the next gen air traffic management system: trajectory based Operations," *Work*, 41(Supplement 1), 2012, pp. 4514-4522

[20]Bergeron, H. P., "Single pilot IFR autopilot complexity/benefit tradeoff study," *Journal of Aircraft*, 18(9), 1981, pp. 705-706.

[21]Hoh, R. H., Bergeron, H., & Hinton, D., "Practical guidance for the design of controls and displays for single pilot IFR" (No. 831423). SAE Technical Paper, 1983.

[22]Kaber, D. B., and Endsley, M. R. "The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task," *Theoretical Issues in Ergonomics Science* Vol. 5, No. 2, 2004, pp. 113-153.

[23]Parasuraman, R., & Byrne, E.A. (2003). "Automation and human performance in aviation," *Principles of Aviation Psychology*. P. Tsang and M. Vidulich, (Eds), Erlbaum, Mahwah, NJ, 2003, pp311-356

[24]Gariel, M., "Toward a graceful degradation of air traffic management systems". PhD Thesis. Georgia Institute of Technology, USA, 2010.

[25]Sheridan, T. B., "Next generation air transportation systems: Human-automation interaction and organizational risks," *Proceedings of the 2nd Symposium on Resilience Engineering* November 8th-10th, Juan-les-Pins, France, 2006, pp. 272-282

[26]Mondoloni, S., Swierstra, S., & Paglione, M., "Assessing trajectory prediction performance-metrics definition," *24th Digital Avionics Systems Conference* (Vol. 1), October, Washington, DC, USA, 2005, pp. 3-C

[27]Hollnagel, E., Martinie, C., Palanque, P., Pasquini, A., Ragosta, M., Rigaud, E., & Silvagni, S., "System Performance under Automation Degradation" (WP-E project SPAD). *First SESAR Innovation Days*, 29 November – 1 December, Toulouse, France, 2011.

[28]Landry, S. J., Archer, J., & Nguyen, N., "Enumeration of National Airspace System uncertainties within an agent-based, state-based model," *AIAA Aviation Conference*. Los Angeles, CA, 2013.

[29]Klutke, G. A., & Yang, Y., "The availability of inspected systems subject to shocks and graceful Degradation," *IEEE Transactions on Reliability*, 51(3), 2002, pp. 371-374.

[30]Jackson, M. R., "Role of avionics in trajectory-based operations," *IEEE Aerospace and Electronic Systems Magazine*, 25(7), 2010, pp. 12-19.

[31]Nilim, A., El Ghaoui, L., Duong, V., & Hansen, M., "Trajectory-based air traffic management (TBO-ATM) under weather uncertainty," *Proceedings of the 4th USA/Europe air traffic management R&D seminar*, NM, USA, 2001.

[32]Engelland, S. A., & Capps, A., "Trajectory-Based Takeoff Time Predictions Applied to Tactical Departure Scheduling: Concept Description, System Design, and Initial Observations," *Proceedings of the 11th AIAA Aviation Technology, Integration and Operations (ATIO) Conference*, 20-22 September, Virginia Beach, VA, 2011.

[33]Wanke, C., Callaham, M. B., Greenbaum, D. P., & Masalonis, A. J., "Measuring uncertainty in airspace demand predictions for traffic flow management applications," *AIAA Guidance, Navigation and Control Conference*, TX, USA, 2003.

[34]Hollnagel, E., Woods, D. D., & Leveson, N., *Resilience engineering: Concepts and precepts*, UK: Ashgate Publishing Company, 2006.

[35]Reason, P., & Bradbury, H. (Eds.), *Handbook of action research: The concise paperback edition*. UK: Sage Publications, 2006.

[36]Shorrock, S. T., "Errors of perception in air traffic control," *Safety Science*, 45, 2007, pp. 890-904

[37]Morrison, R., & Wright, R.H., "Air traffic control and communications problems: An overview of recent ASRS data," *Proceedings of the Fifth International Symposium on Aviation Psychology*, 1989, 902-907.

[38]Endsley, M. & Rodgers, M. D., "Attention distribution and situation awareness in air traffic control," *Proceedings of the 40th Annual Meeting of the Human Factors Society*, 1996.

[39]Wickens, C. D., Mabor, A. S., & McGee, J. P., *Flight to the Future: Human Factors in Air Traffic Control*, National Academy Press, Washington D.C., USA, 1997.

[40]Gibson, W. H., Megaw, E. D., Young, M. S., & Lowe, E., "A taxonomy of human communication errors and application to railway track maintenance," *Cognition, Technology & Work*, 8(1), 2006, 57-66.

[41]Sexton, J. B. & Helmreich, R. L., "Analyzing cockpit communication: The links between language, performance, error, and workload," *Proceedings of the Tenth International Symposium on Aviation Psychology*, Columbus, OH, 1999.

[42]Tajima, A., "Fatal miscommunication: English in aviation safety". *World Englishes*, 23(3), 2004, pp. 451-470

[43]Isaac, A. R. & Ruitenberg, *Air traffic control: Human performance factors*, UK: Ashgate publishing company. 1999.

[44]Pape, A. M., Wiegmann, D. A., & Shappell, S., "Air traffic control (ATC) related accidents and incidents: A human factors analysis," *Proceedings of the 11th International Symposium on Aviation Psychology*, Columbus, OH, The Ohio State University, 2001.

[45]Nunes, A., & Laursen, T., "Identifying the factors that contributed to the Überlingen Midair Collision," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 48, No. 1), Los Angeles, CA: SAGE Publications, 2004, pp. 195-198

[46]Redding, R. E., "Analysis of operational errors and workload in air traffic control," *Human Factors and Ergonomics Society Annual Meeting Proceedings*, 36(17), 1992, 1321-1325

[47]Stager, P., Hameluck, D., & Jubis, R., "Underlying factors in air traffic control incidents," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 33, No. 2). SAGE Publications, 1989, pp. 43-46

[48]Bonini, D., "ATC do I trust thee?: Referents of trust in air traffic control," *CHI'01 Extended Abstracts On Human Factors In Computing Systems*, ACM, 2001, pp. 449-450

[49]Eidelkind, M., & Papantonopoulos, S., "Operator trust and task delegation: Strategies in semi-autonomous agent systems," *Human-Automation Interaction: Research and Practice*, Erlbaum Associates, 1997.

[50]Muir, B. M., "Trust between humans and machines, and the design of decision aids," *International Journal of Man-Machine Studies*, 27(5-6), 1987, 527-539

[51]Wickens, C. D., "Situation awareness and workload in aviation," *Current Directions in Psychological Science*, 11(4), 2002, pp. 128-133

[52]Muir, B. M., & Moray, N., "Trust in automation: part II, experimental studies of trust and human intervention in a process control simulation," *Ergonomics*. 37(11), 1996, pp. 1905-1922

[53]Mosier, K. L., Skitka, L. J., & Korte, K. J., "Cognitive and social psychological issues in flight crew/automation interaction," M. Mouloua, & R. Parasuraman (Eds.), *Human performance in automated systems: Current research and trends*, Hillsdale NJ: Erlbaum, 1994

[54]Foyle, D. C., Hooey, B. L., Bakowski, D. L., Williams, J. L., & Kunkle, C. L., "Flight deck surface trajectory-based operations (STBO): Simulation results and ConOps implications," *Ninth USA/Europe Air Traffic Management Research and Development Seminar* (Paper 132), EUROCONTROL/FAA. Berlin, Germany, 2011.

[55]Perrow, C., Normal accidents. Basic Books Inc.: New York New York, USA, 1999.

[56]Marais, K., Dulac, N., & Leveson, N., "Beyond normal accidents and high reliability organizations: The need for an alternative approach to safety in complex systems," *Engineering Systems Division Symposium*, Massachusetts Institute of Technology, Cambridge, MA: MIT, 2004, pp. 29-31

[57]Johnson, C. W., "Reasons for the failure of incident reporting in the healthcare and rail industries," *Components of System Safety: Proceedings of the 10th Safety-Critical Systems Symposium*, Berlin: Springer Verlag, 2002, pp. 31-60.

[58]Shorrock, S. T., & Kirwan, B., "Development and application of a human error identification tool for air traffic control," *Applied Ergonomics*, 33(4), 2002, pp. 319-336

[59]Bellamy, L. J., Ale, B. J., Geyer, T. A. W., Goossens, L. H., Hale, A. R., Oh, J., & Whiston, J. Y., "Storybuilder—A tool for the analysis of accident reports," *Reliability Engineering & System Safety*, 92(6), 2007, pp. 735-744

[60]Ale, B. J. M., Bellamy, L. J., Roelen, A. L. C., Cooke, R. M., Goossens, L. H. J., Hale, A. R., & Smith, E., "Development of a causal model for air transport safety," *ASME 2005 International Mechanical Engineering Congress and Exposition*, Kolowrocki (Ed.), Advances in Safety and Reliability, Taylor and Francis Group, London, 2005, pp. 107-116

[61]Rasmussen, J., "Information processing and human-machine interaction; An approach to cognitive engineering," *Series in System Science and Engineering*. Amsterdam: North Holland, 1986.

[62]Edwards, T., Sharples, S., Kirwan, B., Wilson, J.R., "Identifying Markers of Performance Decline in Air Traffic Controllers," Di Bucchianico, G., Vallicelli, A., Stanton, N.A., Landry, S.J. (eds.) *Human Factors in Transportation: Social and Technological Evolution Across Maritime, Road, Rail, and Aviation Domains*, 2016.

[63]Morelli, E. A., & Smith, M. S., "Real-time dynamic modeling: data information requirements and flight-test results," *Journal of Aircraft*, 46(6), 2009, pp. 1894-1905

[64]Möller, N., & Hansson, S. O., "Principles of engineering safety: risk and uncertainty reduction," *Reliability Engineering & System Safety*, 93(6), 2008, 798-805

[65]Chen, J. T., Ganji, M., Krozel, J., Kicinger, R., Yang, S., & Mitchell, J. S., "Modeling off-nominal events and mitigation strategies for super density operations," *IEEE/AIAA 31st Digital Avionics Systems Conference* (DASC),Williamsburg, Virginia, USA, 2012, pp. 3A4-1

[66]Histon, J. M., Hansman, R. J., Gottlieb, B., Kleinwaks, H., Yenson, S., Delahaye, D., & Puechmorel, S., "Structural considerations and cognitive complexity in air traffic control," *Digital Avionics Systems Conference* (Vol. 1) Irvine, CA, USA, 2002, pp. 1C2-1.

[67]Graziani, I., Berberian, B., Kirwan, B., Le Blaye, P., Napoletano, L., Rognin, L., & Silvagni, S., "Development of the Human Performance Envelope Concept for Cockpit HMI Design," *HCI-Aero 2016 International Conference on Human-Computer Interaction in Aerospace*, 2016.